Evaporation of accretion disks around black holes: the disk-corona transition and the connection to the advection-dominated accretion flow

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ABSTRACT

We apply the disk-corona evaporation model (Meyer & Meyer-Hofmeister) originally derived for dwarf novae to black hole systems. This model describes the transition of a thin cool outer disk to a hot coronal flow. The mass accretion rate determines the location of this transition. For a number of well studied black hole binaries we take the mass flow rates derived from a fit of the advection-dominated accretion flow (ADAF) model to the observed spectra (for a review see Narayan, Mahadevan, & Quataert) and determine where the transition of accretion via a cool disk to a coronal flow/ADAF would be located for these rates. We compare with the observed location of the inner disk edge, as estimated from the maximum velocity of the H_α emission line. We find that the transition caused by evaporation agrees with this in stellar disks. We also show that the ADAF and the "thin outer disk + corona" are compatible in terms of the physics in the transition region.

Subject headings: accretion, accretion disks—binaries: general—black hole physics—galaxies: nuclei

1. Introduction

How gas falls on to a black hole has been studied intensively since decades and various aspects have been worked out as the two-temperature model (Shapiro, Lightman, & Eardley 1976) and the ion torus model (Rees et al. 1982). In recent years the features of an advection-dominated accretion flow (ADAF) (e.g. Narayan & Yi 1995a, 1995b; Abramowicz et al. 1995, 1996; review Narayan, Mahadevan, & Quataert 1998) have further been investigated. This physics has been used successfully to model both spectra and luminosities in black hole binaries and low luminosity galactic nuclei. Many of these investigations require the coexistence of an inner ADAF and an outer standard thin disk, as proposed by Narayan et al. (1996). Observations indicate that the transition from the cool thin disk to the hot ADAF occurs at hundreds to thousands of gravitational radii. Recently Blandford & Begelman (1999) proposed to modify the ADAF solutions by including a powerful wind ((adiabatic inflow-outflow solutions [ADIOSs]).

It is generally argued that the mass accretion rate determines the transition radius (Esin et al. 1998). Several suggestions have been made to explain such a transition (Narayan & Yi 1995b, Honma 1996, Ichimaru 1977 and Igumenshchev, Abramowicz, & Novikov 1998). The evaporation of matter provides a natural explanation for the transition from a cool disk to a hot coronal flow. With the evaporation model the location of the transition is determined. This "thin outer disk + corona" configuration was suggested and investigated by Meyer & Meyer-Hofmeister (1994). The evaporation model describes how a hot self-sustained coronal layer is built up above the cool inert disk that is fed by matter from the disk underneath. The vertical structure of the corona establishes itself in the balance between heat generation, wind losses, and radiation losses at the coronal-chromospheric transition layer.

The aim of the present investigation is to see whether the transition from a cool disk to a hot coronal flow can give a consistent picture when combined with the ADAF model. The same question can be raised in connection with ADIOSs (Blandford & Begelman 1999) once such a model is worked out in more detail. In Sect. 2 we give a short description of the physics of the evaporation. In Sect. 3 we compare our resulting transition radii with those used for the ADAF spectral fit for a number of well studied X-ray binaries and the galactic nucleus M 87. We consider the physical transition to a hot flow/ADAF for disks with relatively low accretion rates. Discussion and conclusion are given in Sect. 4 and Sect. 5.

2. Implications from evaporation and the determination of the transition radius

A cool disk in the potential well of an accreting compact object loses mass into a corona. This coronal evaporation flow physically results from the following mechanism. The hot corona above the cool atmosphere conducts heat downwards by electron conduction. At the bottom the temperature decreases from the coronal value to a low chromospheric value, heat conduction becomes inefficient, the thermal heat flow has to be radiated away. The efficiency of radiation depends on the square of the particle number density. There is an equilibrium established between heating by conduction and cooling by radiation. In the stationary state this establishes an equilibrium pressure at the interface between the chromosphere and the corona. So the coronal accretion flow continuously drains mass from the corona towards the central object. The matter is resupplied by evaporation from the surface of the underlying cool disk.

The evaporation rates were calculated numerically in detail by Liu, Meyer, & Meyer-Hofmeister (1995) and included in disk evolution for dwarf novae by Liu, Meyer, & Meyer-Hofmeister (1997). The applicability to black hole sources is discussed in Meyer-Hofmeister & Meyer (1999a, 1999b). The model gives the evaporation rate as function of radius and central mass. We measure mass in units of solar masses, $M = m\mathrm{M}_\odot$, radii in units of Schwarzschild radii, $R = r\mathrm{R_s}$, $\mathrm{R_s} = \frac{2GM}{c^2} = 2.95 \times 10^5 m\,\mathrm{cm}$, and mass accretion rates in Eddington units, $\dot M = \dot m \dot M_{\mathrm{Edd}}$, $\dot M_{\mathrm{Edd}} = \frac{L_{\mathrm{Edd}}}{0.1c^2} = 1.39 \times 10^{18} m\ \mathrm{g\,s^{-1}}$. This yields

$$\dot m_{\mathrm{evap}} \approx 30 m^{0.17} r^{-1.17} \tag{1}$$

where r denotes the inner radius of the thin outer disk. This rate depends on the distance to the central object. The closer the disk reaches to the compact object, the stronger is the evaporation. The balance between the mass flow in the thin disk and the mass evaporation determines where the transition into the coronal flow occurs (see also Mineshige et al. 1998). In stationary accretion the equality $\dot m_{\mathrm{evap}} = \dot m$ together with the dependence of the evaporation rate

on r gives the size of the inner hole, that is the transition radius, $r_{\rm tr}$,

$$r_{\rm tr} = 18.3 m^{\frac{0.17}{1.17}} \dot{m}^{-\frac{1}{1.17}} \qquad (2)$$

This relation shows that the transition radius is determined by two parameters, the mass accretion rate $\dot{m}$ and the mass of the central object m, the dependence on m is quite weak. In Figure 1, we show the transition radius as a function of the mass flow rate, determined according to Eq.(2), for rates $\dot{m}$ relevant for stellar black hole accretion.

3. Consistency of the thin outer disk + corona model and the ADAF model

3.1. Methods of comparison

We discuss whether the two concepts, the transition from a cool outer disk to a hot coronal flow and an ADAF close to the black hole, put together can provide a consistent picture of the physics in accretion disks around black holes and in galactic nuclei. We assume here that all matter that evaporates to a coronal flow (except for a small fraction of wind loss) will flow toward the inner ADAF since the transition radius is always smaller than the capture radius of the black hole. What can be compared or proven together with the observational data? For several sources the observed maximum velocity of the H_α emission line is known and interpreted as belonging to the inner edge of the thin disk. For chosen central mass and inclination the transition radius ${r_{\rm tr}}^{\rm obs}$ follows. Two ways of comparison are possible:

(1) If for a source the mass flow rate is known from the ADAF spectral fit (which uses the transition radius ${r_{\rm tr}}^{\rm obs}$) this value $\dot{m}^{\rm ADAF}$ can be taken to compute the transition radius $r_{\rm tr}$ from the thin outer disk + corona model. This comparison is performed in this letter for a number of well studied stellar and galactic X-ray sources. First results for the soft X-ray black hole transient sources A0620–00 and V404 Cyg were derived by Meyer (1999).

(2) If a complete evolution of the stellar disk during quiescence including evaporation in a consistent way is computed, the mass flow rate $\dot{m}^{\rm corona}$ and the transition radius $r_{\rm tr}$ are known at all times. These values can then be compared with ${r_{\rm tr}}^{\rm obs}$ and $\dot{m}^{\rm ADAF}$ (Meyer-Hofmeister & Meyer 1999a, 1999b). Such a comparison takes into account further constraints as outburst recurrence time of the binary and the amount of matter stored in the disk between the outbursts, estimated from the outburst energy. Meyer-Hofmeister & Meyer (1999a, 1999b) followed the disk evolution for A0620-00 and found agreement for their values $\dot{m}$ and $r_{\rm tr}$ with ${r_{\rm tr}}^{\rm obs}$ and $\dot{m}^{\rm ADAF}$.

3.2. Comparison with observations

In Table 1 we list all the black hole X-ray binaries together with one example of galactic nuclei, M 87, for which observations provide an estimate for the transition radius and for which the accretion rates have been derived using the ADAF model, and we compare these with our results for $r_{\rm tr}$. We plot transition radii as a function of mass accretion rate in Figure 1.

A0620-00: The range of possible black hole masses of the soft X-ray transient A0620-00 is m=4.4 to 12, depending on the orbital inclination i, often $m = 6.1$ is taken. The transition radius was estimated on the basis of the largest velocity, $v_{\rm max}$, seen in the H_α emission line from the thin disk, $r_{\rm tr}^{\rm obs} = \frac{1}{2}\left(\frac{c \sin i}{v_{\rm max}}\right)^2$. This value should be an upper limit for the transition to an ADAF. For $m = 6.1$ a satisfactory fit of the spectrum is found with the value $\dot{m} = 9.7 \times 10^{-4}$ (Narayan et al. 1997, model 1). For this value, the transition radius $\log r_{\rm tr} = 3.95$ follows from our model, close to the observationally derived value $\log r_{\rm tr}^{\rm obs} = 3.8$.

V404 Cyg: The parameters of V404 Cyg are well constrained as $m = 12$, $i = 56°$. The H_α emission line indicates a maximal transition radius $\log r_{\rm tr}^{\rm obs} = 4.4$. A typical accretion rate determined by the ADAF fit is $\dot{m} = 4.6 \times 10^{-3}$ (Narayan et al. 1997, model 1 and 6), for which we derive the transition radius $\log r_{\rm tr} = 3.4$. A change of rates $\dot{m}$ by a factor of about 2 gives also a satisfactory spectral fit. In Narayan et al. (1998, Fig. 8) a smaller value is given, $\dot{m} = 2 \times 10^{-3}$, for which we get $\log r_{\rm tr} = 3.7$.

GRO J1655-40: For this system the primary mass $m = 7$ is well determined, but the derivation of a transition radius from the H_α emission line profiles is difficult because of the blended spectrum of the secondary. During the early outburst GRO J1655-40 showed a 6 day delay of the X-rays compared to the optical radiation, a very interesting feature in connection with evaporation. Such a long delay, analogous to the UV delay in dwarf novae, can not be explained by simple thin disk instability models. As pointed out by Hameury et al. (1997), a thin disk which reaches inward to only a certain transition radius can explain the delay. Their computations include evaporation in

a simplified manner and model the X-ray delay. The transition radius is estimated as $r_{\rm tr} = 5 \times 10^3$. It is clear that the transition of the cool disk to a coronal flow, which is also present at the onset of the outburst, can afford to have this hole first filled in with matter by diffusion before the change of the hot state can proceed inwards to the X-ray emitting region. A detailed modeling of the quiescent state spectrum based on the "ADAF plus a thin disk model" (Hameury et al. 1997) yielded $\dot{m}$ ranging from 3.5 to 3.8×10^{-3}. This gives $\log r_{\rm tr} \approx 3.5$, which is close to the value $\log r_{\rm tr}$=3.7 estimated from outer-disk-stability arguments by Hameury et al. (1997) and is in agreement with the diffusion time necessary to explain the observed delay of X-rays.

M 87: We calculated numerically, in stead of Eq. (2) for stellar objects, the transition radius of this object as a preliminary application of the thin outer disk + corona model to galactic nuclei. Reynolds et al. (1996) studied advection-dominated accretion in the massive black hole M 87. The fit to the broad band spectrum for $m = 3 \times 10^9$ is satisfactory for values $\dot{m} = 10^{-3.5}$ to 10^{-3}. Again, a thin disk was not taken into account. For $\dot{m} \approx 10^{-3}$ our numerical calculations show a transition radius $\log r_{\rm tr}$=3.9. Reynolds et al. (1996) had taken a much smaller outer radius, $\log r_{\rm tr}$=3, pointing out that their fit of the spectrum is rather insensitive to the outer radius of the advection-dominated region. This is due to the lower temperatures further out. But spectra obtained with the Faint Object Spectrograph on the Hubble Space Telescope show emission lines broadened to FWHM $\approx 1700 \mathrm{km\,s^{-1}}$, interpreted as from a thin disk of ionized gas in Keplerian rotation (Harms et al. 1994), images of the disk show an inclination angle $i = 42°$ (Ford et al. 1994). This indicates that the thin disk reaches at a distance of $\log r = 3.84$, which is close to what is expected from our estimates.

3.3. Compatibility of the two models in the transition region

In the transition region shown above, $r_{tr} > 10^3$, electrons are still efficiently coupled with protons, and the ADAF can be treated as one-temperature and quasi-Keplerian rotation. Then the vertical averaged equations governing the ADAF are (Narayan et al. 1998),

$$\frac{d}{dR}\left(\rho R H v_r\right) = 0 \tag{3}$$

$$c_s \approx \Omega H \tag{4}$$

$$v_r \frac{d\left(\Omega R^2\right)}{dR} = \frac{1}{\rho R H}\frac{d}{dR}\left(\nu \rho R^3 H \frac{d\Omega}{dR}\right) \tag{5}$$

$$\rho v_r T \frac{ds}{dR} = q^+ - q^- \tag{6}$$

where all the quantities have their standard meanings.

On the other hand, at the transition radius there is no cool disk and the evaporation doesn't work any more. Thus, the vertical component of gas velocity and the heat conduction approach zero, the equations in the thin outer disk + corona model (Meyer & Meyer-Hofmeister 1994) are then simplified as,

$$\nabla \cdot \rho \mathbf{v} = 0 \tag{7}$$

$$\frac{dP}{dz} = -\rho \frac{GMz}{\left(R^2+z^2\right)^{3/2}} \Rightarrow c_s \approx \Omega H \tag{8}$$

$$v_r \approx -\alpha c_s^2/\Omega R \tag{9}$$

$$\frac{3}{2}\alpha P \Omega - n_e n_i \Lambda\left(T\right) + \frac{2\rho v_r}{R}\left(\frac{v^2}{2} + \frac{\gamma}{\gamma-1}\frac{P}{\rho} - \frac{GM}{R}\right) = 0 \tag{10}$$

Comparing these two sets of equations, one can see that the first two equations are the same. Joining eq.(3) and eq.(5) and taking $\nu = \frac{2}{3}\alpha c_s H$, we obtain $v_r = -\alpha c_s^2/\Omega R$, which is exactly the third equation of the thin outer disk + corona model. q^+ and q^- in the energy equation of the ADAF correspond to the viscous heating rate $\frac{3}{2}\alpha P \Omega$ and the optically thin cooling rate $n_e n_i \Lambda(T)$, respectively, in the energy equation of the thin outer disk + corona. The entropy term $\rho v_r T \frac{ds}{dR}$ can be developed as follows:

$$\begin{aligned}
\rho v_r T \frac{ds}{dR} &= \rho v_r \left[\frac{d\left(\frac{\gamma}{\gamma-1}\frac{P}{\rho}\right)}{dR} - \frac{1}{\rho}\frac{dP}{dR}\right] \\
&= \rho v_r \frac{d}{dR}\left(\frac{v^2}{2} + \frac{\gamma}{\gamma-1}\frac{P}{\rho} - \frac{GM}{2R}\right)
\end{aligned}$$

where we replaced $\frac{1}{\rho}\frac{dP}{dR}$ by $-v_r\frac{dv_r}{dR}$ from the radial Euler equation. In a similar way to the thin outer disk + corona, let $\frac{d}{dR} \sim -\frac{2}{R}$, then the energy equation of the ADAF has the same form as that of the thin outer disk + corona model except for a factor of 1/2 in the term $\frac{GM}{R}$. Therefore, we can expect a smooth transition from an thin outer disk + corona to an ADAF.

4. Discussion

X-ray binaries: The dependence of the transition from corona to thin disk on $\dot{m}$ allows to understand the different regimes of a cool outer disk together with a coronal flow/ADAF. For low $\dot{m}$ the transition occurs at a large radius, the thin disk is easily evaporated and the coronal flow/ADAF is dominant in a large region of the accretion disk (Our examples, given in the last section, belong to this regime). For intermediate $\dot{m}$, the mass supply by accretion can balance the evaporation farther in. At high $\dot{m}$, the mass supply rate may be larger than the evaporation rate everywhere and the thin disk or a slim disk (Abramowicz et al. 1988) then extends all the way down to the last stable orbit. This agrees with the picture proposed by Esin et al. (1997, 1998) and Narayan et al. (1998). Table 2 illustrates the regimes of different spectral states of X-ray binaries according to the relation (Eq.2) between mass accretion rate and transition radius. There is only one adjustable parameter, $\dot{m}$, that determines the spectral state in our scenario.

Galactic nuclei: Observations of galactic nuclei show a wide range of luminosities, from $L < 10^{37}\mathrm{ergs\,s^{-1}}$ for our Galactic Center to $10^{48}\mathrm{ergs\,s^{-1}}$ for luminous quasars. The underluminous galactic nuclei can be understood as presently accreting via an ADAF (Narayan et al. 1998). Since the physics of the evaporation process is very similar in stellar sources and galactic nuclei, we investigated the applicability of the thin outer disk + corona model for the latter. Numerical results show that the predicted transition radius for M87 is consistent with observations using the accretion rate derived from the ADAF fits. We expect that the evaluation of the transition radius for low luminosity AGNs could be possible.

5. Conclusions

We investigated whether the ADAF model and the thin outer disk + corona model could be a consistent description of the accretion process. It is not clear at all, since these two concepts describe different physics in different regions. The ADAF model allows to derive mass accretion rates from a fit to the observed spectrum. The position of the inner edge is estimated from the observed maximal velocity of the H_α emission lines. We take these derived mass accretion rates and evaluate the transition between outer thin disk and coronal flow according to disk evaporation (Meyer & Meyer-Hofmeister 1994). For both X-ray binaries and the galactic nucleus M 87 the deduced transition radii are in agreement with those inferred from observations. Moreover, we showed that the ADAF and the thin outer disk + corona are compatible in terms of the physics in the transition region. These support both, the ADAF interpretation and the evaporation model. A detailed, more constrained investigation for the evolution of the cool disk in A0620-00 by Meyer-Hofmeister & Meyer (1999a, 1999b) confirms this agreement.

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Table 1: The transition radii for black hole-accreting systems

Object	m	$\dot{m}$	$\log r_{\rm tr}$	$\log r_{\rm tr}^{\rm obs}$
A0620-00	6.1	9.7×10^{-4}	3.95	3.8
V404 Cyg	12	4.6×10^{-3}	3.42	≤ 4.4
GRO J1655-40	7	3.5×10^{-3}	3.48	3.7
M 87	3×10^{9}	10^{-3}	3.90	3.84

Notes to the table:
m: Black hole mass in units of solar mass
$\dot{m}$: Mass accretion rate in units of Eddington rate, which generally varies by a factor of 2 for the ADAF fit
$r_{\rm tr}$: The transition radius predicted by our model
$r_{\rm tr}^{\rm obs}$: The ADAF-thin disk transition radius derived from observations

Table 2: The relation between accretion rate and transition radius for various spectral states of X-ray binaries

Spectral state	m	$\dot{m}$	$\log r_{\rm tr}$
quiescent state		$\lesssim 0.01$	> 3
low state	3–12	$0.01-0.1$	$2-3$
intermediate state		~ 0.1	~ 2
high state		> 0.1	< 2

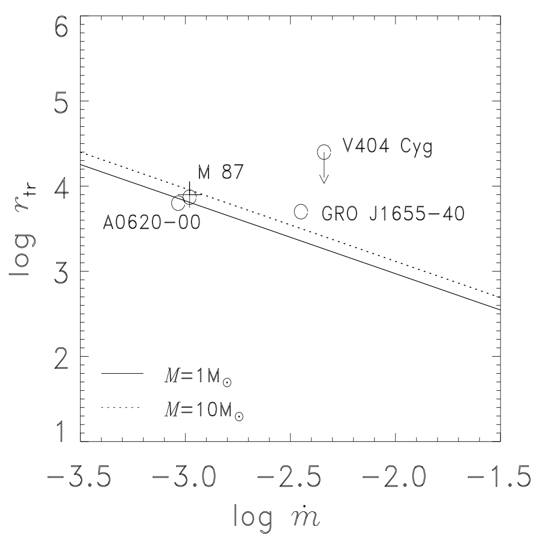

Fig. 1.— The lines show the transition radius $r_{\rm tr}$ as a function of accretion rate $\dot{m}$ for stellar black hole masses M=1 M$_\odot$ and 10 M$_\odot$, respectively, according to the thin outer disk + corona model. The circles show the transition radii derived from observations. The cross is the predicted transition radius for the galactic nucleus M 87. The values are given in Table 1.